9. APPLICATIONS OF RISK ANALYSIS TO SPACE LAUNCH OPERATIONS

9.1 LAUNCH RISK ANALYSIS OBJECTIVES

Risk Analysis is not an end in itself, but rather a means to accomplish other goals: the identification of hazards and the assessment and quantification of risk provide insight to the overall acceptability of a program, such a commercial space launch campaign, from operational, regulatory or societal viewpoints. If the associated risk level appears unacceptably high to the public agency sponsoring or regulating the activity, the analysis can provide information needed to control and reduce the risk. The whole Range Safety Control process (see Ch.2, Vol.1) is predicated on risk avoidance, minimization of accident impacts and the protection of population centers (see also Ch. 10). Risk values related to space-launch activities may be generally categorized in two ways: (1) the probability of vehicle failure, including all possible failure modes, that could lead to debris impact events and their probabilities; and (2) consequence estimation, i.e., expected casualties or damage. The probability of debris impacts generally means that at least one object impacts in a specific area. The casualty estimation generally used is one of two types: (1) the probability of casualty, defined as the probability of one or more persons sustaining an injury; or (2) the expected number of casualties, defined as the number of persons expected to sustain an injury as a result of at least one object impact in a specific area. These concepts have also been discussed and illustrated in the context of Range Safety destruct actions (Ch. 2, Vol.1 and Ch. 10) and re-entry hazards (Ch. 7, Vol.2).

The following is a list of general uses and applications of Risk Analysis in the context of space mission planning, approval and implementation:

- A risk study can serve as a tool in the total decision making process for the Range or the sponsoring organization.

- Excessive risk may reveal the need for a Flight Termination System (FTS) or other program restrictions (e.g., restrict land overflight or launch azimuths).[29,32]

- Results are a tool to help underwriters price commercial space insurance.

- Results may indicate the requirement that an existing or pre-designed FTS or other critical ELV system be redesigned, if such a redesign can significantly reduce these risk levels via greater safety margins or introducing redundancies.[33]

- Results may indicate the need for evacuation of Range personnel, enforcement of roadblocks, restricted sea lanes or airspace, movement of critical equipment, call-up/purchase of additional real estate or justification for currently controlled land.[2 b]

- Results might show the necessity to modify the support plans for other Range support elements permitted within the evacuated area, i.e., manned optical tracking sites.

- Results can be used in the development of ELV flight safety operational support plans to include procedures, destruct criteria and whole vehicle versus destruct case (many fragments) impact decisions.[10,11]

- Results can be used to alert the Range or Sponsor management to excessive on-site or public risk exposure levels for given launches or total programs. It is then the decision of management on which course to proceed.[17]

- Results might identify launch scenarios and patterns that require mission operational procedure changes or hardware redesign/modification to allow the selection of less hazardous options, based on cost/benefit or operational constraints and priorities.[18]

- Results may indicate the need to construct new facilities in cases where it is not acceptable to use existing facilities.[20]

- Results might reveal the need and advantage of providing positive protection for nonevacuated personnel (shelters, barricades, bunkers, blockhouses, etc.) and critical equipment required in the evacuated area.[20]

- Results can be used to establish and define limiting criteria which may be used both quantitatively and qualitatively. Impacts of single launches or cumulative impacts of space launch programs can be compared in this manner.[19,32]

- Risk studies can provide documented evidence that specific hazards were considered in an objective and rational manner in developing operation plans.[8-13]

- "Risks to launch" results identify the reliability of the Range support equipment and personnel and can be used for the following purposes:[19,32]

    a. Identify high risk from inadequate Range support elements and, therefore, assist in increasing total reliability and reducing hazards involved in launching.

    b. Increase Range operational safety and supportability.

    c. Increase Range capability and attractiveness to potential users.

A general method that satisfies all possible analytical problems related to space operations does not exist, as discussed in Ch. 8. Historically, the National Ranges have developed their own computer programs for risk studies and analyses, as appropriate to specific tests, launch vehicle systems or Range operation problems. Although no standardization exists at present between the Ranges regarding methodology, computer programs and analytical tools (mainly because of different siting and demographics, but also because of specialized uses of each Range), the major types and elements of space risk analysis do recur. Moreover, there are technology transfer and standardization efforts in progress at ESMC and WSMC. A typical Risk Analysis requires five basic categories of data:

1. Systems failure modes and their probabilities.
2. Impact probabilities and distributions resulting from failures or normal launches.
3. A measure of lethality of impacting debris.
4. Location and nature of population and structures placed at risk by the mission.
5. Launch plans, subject to Ground Safety and Range Safety constraints.

Various elements of these categories may be considered in development of a Risk Analysis for a space launch vehicle, mission and/or operation.

The end result of a Risk Analysis for a specific launch and orbital mission is valid only to the degree of reliability and completeness of the inputs and their applicability to a given launch vehicle or site. A result valid for one Range may be meaningless for another, because flight corridors, destruct criteria and impact limit lines are designed to be site-specific and are tied to the launch azimuth. Risk Analysis results may have orders of magnitude uncertainties, since they generally reflect compounded uncertainties in both initial and boundary conditions, i.e., in assumptions, modeling simplifications, approximations and possible errors of omission in the anticipated failure modes and times. Risk studies, as applied to date to space operations, have been used as aids in the decision-making process in conjunction with other factors (proven Range capability, experience, precedent, national interests and priorities, etc.). Therefore, there are no general, uniform and firmly established acceptable risk levels for space operations,[1] although policy decisions and risk acceptability guidelines have often been based on matrix-type risk assessments (Ch. 10).[3-6]

Several mission agencies have developed such matrix-type risk classification, ranking and evaluation procedures, which facilitate the objective definition of acceptable and unacceptable ranges of risk. The formal DOD risk matrix for space launches is illustrated in Ch.10.[5] The DOD qualitative hazard probability classification ranges from Level A (frequent), B (probable), C (occasional), D (remote), to E (improbable). Similarly, the consequence severity categories, which account for damage, injuries or both are: I, catastrophic; II, critical; III, marginal; and IV, negligible. Hazard analyses attempt to rank failures and accidents in a two-dimensional probability/consequence matrix and assign a hazard index to each accident accordingly (e.g. 1A, 2E, 4D). Then these can be judged acceptable, undesirable or unacceptable according to suggested criteria.[3] The logic flow of a general risk assessment procedure, as it typically applies to DOD space operations, is shown in Figure 9-1.[16]

NASA has, however, established explicit launch safety criteria and numerical risk acceptability goals, as detailed in Sec. 9.2.[7] NASA uses a mishap (or accident) severity classification consisting of three hybrid categories: A - causes death, damage exceeding $500,000 or destruction of space hardware and/or spacecraft; B - causes permanent disability to one or more people, damage valued at $250,000-500,000; C - causes only occupational injuries and/or < $250,000 damage.[7a-c] NASA has traditionally required Safety Assessment Reports (SAR) for all missions that may deviate from proven safety procedures and set safety criteria and standards.

DOE has also developed and used extensively risk ranking matrix methodologies, that combine and trade off the frequency and the severity of an event. However, the severity of consequence classes, A, B and C from worst to least, differ by loss type fatalities, property loss, or environmental pollution effects). The accident frequency scale ranges from probable (1-100 years return period), to reasonably probable (100-10,000 years), remote 10 thousands to ten million year) and to extremely remote beyond this return period for the accident or event.

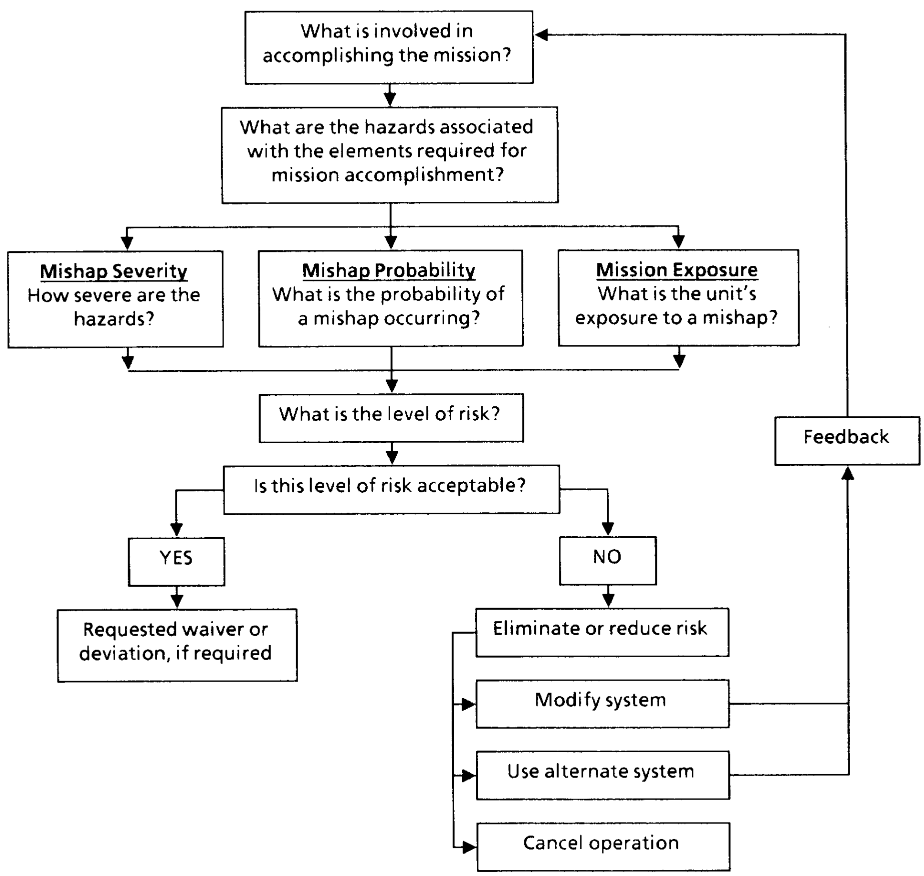

FIGURE 9-1. GENERALIZED RISK ASSESSMENT PROCEDURE (Ref. 16)

Note that the probability of an event corresponding to a 100 years return period is 10^{-2} per year. The matrix risk ranking scheme permits first order (probable and severe) risks to be defined, down to fourth order (remote - C, or extremely remote -B events).[37]

9.1.1 System Failure Modes and Probabilities

Launch Vehicle physical data used may include:

- Propellants
- Explosive/fuel chemical properties
- Fragmentation characteristics
- Mass
- Shape
- Ballistic coefficients
- Flight dynamics
- Flight Termination System (FTS)
- Guidance and control
- Stage burn times and separation characteristics
- Lethality of debris, as represented by the Lethal Area

The failure modes and associated probability of failure are required if other than a normal launch is addressed.[9,10] Estimates for failure mode probabilities are typically based upon knowledge of the vehicle's critical systems and expert assessment of their reliability combined with historical data, when available.[8-11,17,18] The single point (critical) failure systems, such as the FTS, are designed, tested and certified to very high reliability standards: at WSMR the FTS reliability quoted for a non- redundant FTS required for a typical sub-orbital research or sounding rocket system is .997 at a 95% confidence level. However, higher reliabilities with failure probabilities of 10^{-6} apply to redundant FTS systems required for large ELV's. Typically, FTS designs are required to be "single fault tolerant" i.e., redundant.[6]

The total probability of an ELV operational failure includes contributions from all foreseeable failure modes which can lead to either thrust termination or malfunction turns. The occurrence of failures during a critical time interval, such as the boost phase or stage separation, permits the estimation of failure rates versus time into flight. Illustrative figures for the two major failure modes for Titan 34D as a function of time into flight are given in Table 9-1. These figures are based on an analysis of past launch performance data for the Titan family of vehicles, corrected for learning, i.e., the improvements in manufacturing, assembly and operational procedures which take place after a failure is diagnosed, analyzed and fixed.[38,39]

TABLE 9-1. TITAN III/34D FAILURE RATES USED AT WSMC*

FLIGHT TIME (sec)	KEY FAILURE RATE ($SEC.^{-1}$) MALFUNCTION TURN	THRUST TERMINATION
0	1.93×10^{-5}	1.93×10^{-5}
60.4	1.93×10^{-5}	1.93×10^{-5}
181.5	1.93×10^{-5}	1.915×10^{-4}
258.5	1.93×10^{-5}	1.915×10^{-4}
259.5	3.14×10^{-5}	9.53×10^{-5}
260.5	6.27×10^{-5}	1.93×10^{-5}
476.0	6.27×10^{-5}	1.93×10^{-5}

* - Based on VAFB/WSMC and historical launch failure data, Reference 39.

9.1.2 Impact Probabilities

The regions or areas exposed to launch operations or accident hazards must be identified (see Ch. 4). These may be subdivided into smaller sections, critical locations of people or buildings that are specified for subsequent risk calculations. All risk analyses require estimates of the probabilities of debris/fragments from failed vehicle impacting within hazardous distances of personnel or structures in the region.[17,23] The probability of an impact, P_i, for a public area requires consideration of all failure chains which could endanger it and always implies an FTS failure whose probability is P_f, given that a critical vehicle failure of probability P_v has occurred.

The design and engineering associated with the development of a system is geared to produce a properly functioning vehicle. As a consequence, there are generally no data defining vehicle performance characteristics after a critical failure has occurred, except environment definition and vehicle response scenarios assumed. These data are required for meaningful risk assessment. To provide such data, several computer models discussed below in Sec. 9.2 have been developed to simulate vehicle responses after a given gross failure mode has occurred.[19] These computer models are used as part of the computational process for generating debris impact probability density functions. These models combine, statistically and dynamically, well defined vehicle data with expert engineering estimates to predict vehicle performance after a failure occurs (e.g., Table 9-1). Sometimes failures that occurred during design verification and system tests can be used to infer in-flight failure behavior. Also, Mishap Reports, which are based on failure diagnostics and accident investigations, help to refine these computer programs or their external data files with field data.[33,34] Failures possible during each launch and flight phase must be considered separately, in order to isolate those with the potential for public safety impacts.

9.1.3 Debris Lethality

An important aspect of the vehicle data problem that must be addressed prior to performing risk calculations is to determine what occurs after vehicle failure and fragmentation (whether on command or spontaneous) leading to ground impact. The number of fragments, their sizes and shapes will ultimately define the hazard and casualty area for a given vehicle or fragment impact (Table 9, Ref. 37b). Debris are characterized by their size, mass, area and ballistic coefficient to determine if they survive re-entry and their terminal velocity at ground impact. The data items which are often developed for this part of the problem include: an impact energy distribution budget, secondary explosive energies available (if any) at impact, secondary fragments which may result from impact (splatter effect) and ricochet probabilities and characteristics.[20,22] Also, the likelihood, severity and extent of toxic vapor clouds, pool fires and blasts are used to calculate hazard areas for the various hazard mechanisms (see also Ch. 5, Vol. 2 and Ch. 10).

9.1.4 The Meaning of Casualty Expectation

The quantity most frequently employed to evaluate the risk associated with the testing and operation of a space launch system is called casualty expectation, E_c. This quantity corresponds to the expected or mean number of casualties or injuries if an ELV is launched according to a specific mission plan. The specific approach to compute casualty expectation is adapted by the National Ranges to fit their specific problems and launch situations.[17-23] In general, E_c is obtained by considering the following quantities:

- The area, A, in which debris impacts can occur, partitioned into A_i subsets of areas.

- The fragment impact probability density (P_i) on A_i produced by a given system failure.
- The hazard area, A_{Hi}, associated with an impact on A_i, is the effective casualty (lethal) area for an impacting piece of debris.
- N_i, the number of people in A_i at risk from debris impacts.
- V, vulnerability, i.e., the likelihood that a structure (hardened or not) within A_{Hi} can be penetrated by debris or that a person can be injured as the result of impact. This is only explicitly factored when estimating risk to off-shore oil platforms and on-site facilities.[17,20]

These quantities are then used in an equation of the form

$$E_c = \sum_{i}^{N} P_i \frac{A_{Hi}}{A_i} N_i$$

The E_c estimate, as a measure of risk for a given test, is often calculated by summing the risk over the hazard area for the test with each element of the sum. These are weighted according to the probability, as a function of time after launch, of the i-th failure mode which may require destruct or lead to vehicle fragmentation (Table 9-2). It must be noted that Ec is not the probability of a casualty, because it can be >1 in special cases. For illustration of the difference, in case of one accident per 1,000 with an average of 5 casualties per accident, Ec is 5/1,000, but the probability of a casualty is 1/1,000.

TABLE 9-2. OVERFLIGHT LAND IMPACT PROBABILITIES & CASUALTY EXPECTATIONS AT ESMC
(Ref 37)

Vehicle	Flight Az. (Deg)	P_I**	E_C*
Titan 34D/Transtage (1)	93	2.2×10^{-5}	2.1×10^{-8}
	97	1.7×10^{-5}	1.2×10^{-8}
	101	1.4×10^{-5}	0.7×10^{-8}
	105	1.1×10^{-5}	1.1×10^{-8}
	109	0.9×10^{-5}	1.5×10^{-8}
	112	0.7×10^{-5}	1.3×10^{-8}
Titan 34D/IUS (2)	40	unknown	1.6×10^{-6}
	44	"	0.4×10^{-6}
	48	"	0.2×10^{-6}
	52	"	0.7×10^{-6}
	56	"	0.3×10^{-6}
	60	"	0.1×10^{-6}
Space Shuttle (3)	39	"	3.5×10^{-7}
	61	"	7.5×10^{-8}
	90	"	1.8×10^{-7}
Atlas Centaur (4)	80	1.5×10^{-2}	9.6×10^{-6}
	90	0.66×10^{-2}	4.0×10^{-6}
	100	0.28×10^{-2}	0.7×10^{-6}
	110	0.14×10^{-2}	1.3×10^{-6}
Delta (5)	95	4×10^{-3}	3.7×10^{-6}
	108	8.1×10^{-4}	8.3×10^{-7}

Notes:

(1) 1982 study. Failure rate for stage thrusting during dwell time over Africa assumed to be 2.3×10^{-5} failures/sec. Ac = 860 sq. ft.

(2) 1978 study. Failure rate for stage thrusting during dwell time over Africa = 2.3×10^{5} failures/sec. A_c = 400 sq. ft.

(3) 1981 study. Failure rate assumed for overflight stage 2.9×10^{-7} failures/sec. As part of same study, NASA estimated catastrophic failure probability for solid rocket motor of 1×10^{-4}; the Range estimated 1×10^{-2}.

(4) Study from mid 1960's with failure probability for Centaur stage = 0.33

(5) Study from mid 1960's with failure probability for Agena stage = 0.108

**P_I = Probability of land impact equal to the product of the dwell time over land with the failure probability of the vehicle stage thrusting during the dwell period.

*E_C = Casualty expectation equals product of P_I, the population density and the area exposed to re-entering fragments.

9.1.5 Population/Structures Data

The major purpose of a launch risk analysis is to determine the magnitude of hazards to personnel and structures posed by a launch and/or total program. Public risk exposure is of concern primarily near the launch site and during the first minute after launch, when, if the vehicle fails, it may veer towards populated areas protected by impact limit lines. The FTS must also fail (a double failure must occur) in order to violate the destruct limits designed to protect the public. The probabilities of such double failures are typically very low, on the order of 10^{-6} to 10^{-8}.[37] Locations of buildings and structures and the distribution of population throughout the area must be known, as well as other facts, including:

- Sheltering capability of occupied structures, i.e., the ability to withstand debris impact and protect against overpressures from explosions or impact kinetic energy conversion;
- Frequently, population distributions may be functions of the time of day or week and may be significant in risk tradeoff studies;
- Risk levels can be directly affected and controlled to some extent by population control, sheltering, Range clearance or by preventing people from entering these areas (e.g., road-blocks).

Based on such an analysis combined with mission profile constraints, the Impact Limit Lines (ILL) beyond which the vehicle and its fragments should not impact are determined for each launch to protect population and structures. Infringement of the ILL warrants a positive destruct action (see Ch.2, Vol.1).

9.1.6 Launch and Mission Planning

The actual implementation of operational plans under launch conditions ultimately determines the actual risk exposure levels on and off-site.[11-13,18] Integral to the analysis are the constraints posed by the following:

- Launch area/Range geometry and siting
- Nominal flight trajectories/profiles
- Launch/release points

- Impact limit lines, whether based on risk to population/facilities or balanced risk criteria.

- FTS and destruct criteria

- Wind/weather restrictions

- Instrumentation for ground tracking and sensing on-board the vehicle

- Essential support personnel requirements.

The Range Safety Group (or its equivalent) typically reviews and approves launch plans, imposes and implements destruct lines and other safeguards, such as NOTAMs (Notice to Airmen), Air Space Danger Area notifications and radio-frequency monitoring (see Ch.2, Vol 1).

The launch (normal and failure) scenarios are modeled and possible system failure modes are superimposed against the proposed nominal flight plan. Hazards and risk resulting from all known or hypothetical failures are summed in the overall E_c for the launch. A range of values (risk envelope) rather than a single probability or casualty expectation value is determined. The hazard to third parties is dependent upon the vehicle configuration, flight path, launch location, weather and many other factors (see Ch.5, Vol.2). It should be possible to tabulate casualty expectations and impact probabilities for a particular range, vehicle and typical flight path, but this information is not easily available in the public domain presently.

9.2 LAUNCH RISK ANALYSIS TOOLS.

9.2.1 Pre-launch Safety Requirements.

Any contractor or launch vehicle manufacturer using a National Range must comply with extensive safety requirements,[4-6] and submit sufficient data regarding the mission trajectory and vehicle performance to support the mission safety evaluation, operational planning and approval.[8-12] A Blast Danger Area around the ELV on the launch pad and a Launch danger Area (a circle centered on the pad with tangents extended along the launch trajectory) are prescribed for each ELV depending on its type, configuration, amount of propellants and their toxicity, TNT equivalents, explosive fragment velocities anticipated in case of an accident, typical weather conditions and plume models of the launch area.

The list of safety documents that a Range User must comply with is a comprehensive set of Ground and Range Safety requirements [5-7,16]. The scope of the effort involved to apply them to mission analysis and approval is well illustrated in a four volume Integrated Accident Risk Assessment Report (IARAR), which includes quality assurance and certification of critical components and subsystems, electro-explosives, hazardous propellants and chemical information, vehicle description and payload/system safety checks.[8] In the case of man-rated space systems, like the Shuttle, the customary safety requirements and the lengthy lead time required for mission planning and approval become even more cumbersome.[29-32] More typical are the mission approval documentation submitted to the Range, such as the Flight Plan Approval and Flight Termination reports illustrated by Refs. 10-13 and 15.

A Flight Safety Plan and supporting data must be supplied by the User to the National Range, prior to mission approval and operational planning.[36] Each launch is evaluated based on:

- Range User data submission requirements from the hazard analysis view point;[18,22]

- launch vehicle analyses to determine all significant failure modes and their corresponding probability of occurrence (FMEA's and Reliability Analyses);[9a,b]

- the vehicle trajectory, under significant failure mode conditions, which is analyzed to derive the impact probability density functions for intact, structurally failed and destructed options;[11-13]

- the vehicle casualty area based upon anticipated (modeled) conditions at the time of impact;[10,13]

- computed casualty expectations given the specific launch and mission profile, population data near the Range and along the ground track.[10,15] Shelters may be provided, or evacuation policies adopted, in addition to restricting the airspace along the launch corridor and notifying the air and shipping communities (NOTAM) to avoid and/or minimize risks;

- an Accident Risk Assessment Report (ARAR) prepared to identify hazards of concern, causes, controls and verification procedures for implementing such controls.[8]

The ESMC and WSMC Range Safety Requirements specify the data submissions expected from Range Users to enable hazard assessments prior to granting launch approval, including:

- determination of significant failure modes and derivation of impact probability density functions(PDF);

- evaluation of casualty area based on vehicle break-up analysis;
- computation of dwell times over land; impact probabilities; casualty expectations based on land area, geography and population densities;
- sample calculations and documentation.

Missions involving nuclear power packs or payloads must qualify based on very stringent safety criteria and are approved only after review by an Interagency Nuclear Safety Review Panel (INSRP). Detailed risk assessments have been performed by NASA, DOE, DOD and their contractors for the INSRP prior being allowed to launch satellites with nuclear power sources such as Radioisotope Thermal Generators (RTG) on-board the STS.[25-28]

9.2.2 Risk Models and Safety Criteria Used at National Ranges.

The Range Safety Group, Range Commanders Council (RSG/RCC) has reviewed a number of the computer models used by five of National Ranges (including the White Sands Missile Range - WSMR, Western Space and Missile Center - WSMC, the Pacific Missile Test Center - PMTC, US Army Kwajalein Atoll - USAKA, and the Armament Development Test Center - ADTC) to assess launch-related risks to on-Range personnel and the public.[1] Different models and computer codes are used at the Eastern (ESMC) and Western (WSMC) Test Ranges, and at the NASA/GSFC Wallops Island Launch Facility (WFF) because launch vehicles, mission objectives and site specifics vary.[7,18,19]

The evaluation of launch associated hazards is based on Range destruct criteria designed to minimize risk exposure to on and off-Range population and facilities. Computer models are used to simulate missions for optimization and approval or run in real time for Range Safety Control Officers to monitor flight performance.

The DOD Ranges do not have published requirements for acceptable levels of public risks, presumably because national security interests can take precedence in testing new launch systems and launching defense payloads and spacecraft. Since launch risk exposure to the public is primarily controlled in real-time by the Range Safety personnel rather than the Range User, the residual and uncontrollable hazards to the public are re-entry hazards due to failures to achieve proper orbit and premature re-entry of the payload.

The NASA/WFF Flight Safety Plan, compares the risks associated with a specific mission to "acceptable risk criteria," such that:

- casualty expectation $\leq 10^{-7}$ for planned or accidental impact and re-entry of any part of the launch vehicle over any land mass, sea or airspace;
- probability of impact with potential damage to private property $\leq 10^{-3}$ (unless an SAR is prepared and approved or a waiver is obtained);
- probability of impact with flight support aircraft (for meteorological monitoring, or tracking support of $\leq 10^{-6}$ (note that other aircraft are excluded by NOTAM and airspace restrictions);
- probability of impact with ships and boats within the impact area (inside a 50 mile radius from the launch points) of $\leq 10^{-5}$. (Some Ranges observe a 20mi. radius;[37b] Wallops Flight Facility surveys out to 100 miles.[40])

From 1961 to 1983, Wallops has experienced 14 launch failures out of over 10,000 sub-orbital launches of sounding rockets, resulting in an observed land impact probability of 2.8×10^{-3}. Of these, only three impacted outside the launch site area (i.e., $P = 6 \times 10^{-4}$). Assuming an average population density of 64 per sq mi., the casualty expectation based on this observed vehicle failure rate is 8×10^{-9}. Similarly, for debris dispersal over water, a ship traffic density of 2.6×10^{-5} per sq. nmi per day was used, resulting in an expected 3.7×10^{-7} probability of a sustainer impacting a ship. For comparison, Wallops threshold ship-impact probability criteria are $\leq 10^{-5}$, corresponding to 20x increased allowance for ship impact.

Range Safety Reports, Safety Analysis Reports (SAR's) and other such probabilistic Hazard Analyses must be prepared by Range Users for Mission Approval at most National Ranges whenever a new launch vehicle configuration (e.g., a Titan with an IUS or Centaur upper stage), an unusually hazardous payload (e.g., a nuclear powered spacecraft) or a trajectory with land overflight are involved (i.e., whenever "deviations" from approved safe procedures, vehicles and programs are filed). Similar reports are needed for US-sponsored launches from foreign territories. Either the User submits the data for the Range to carry out its own hazard analyses or the User prepares such a document on request.[6]

Safety Assessment Reports (SAR's) were typically prepared by NASA GSFC/Wallops Flight Facility (WFF) for sub-orbital launches from foreign territory. Two references are representative of the types of launch hazards of concern and the NASA approach to risk assessment: The SAR for Project CONDOR involved launches in 1983 from Punta Lobos, Peru, using Taurus-Orion, Terrier Malemutes, Nike-Orion, Black Brants and similar sub-orbital vehicles to launch retrievable atmospheric sounding research payloads.[7e-g]

Range Safety Guidelines minimize post-launch risks to the public by imposing a number of restrictions: e.g., no land over-flight corridors are selected if it is possible to have launches and flight paths over water. However, for land-locked launch sites such as WSMR, strict overflight criteria restrict both land and airspace corridors to on-Range and Extended Range areas.[2] There are no intentional off-Range land impacts permitted for any normally jettisoned booster and sustainer casings and sufficient safety margins are provided within the destruct corridor to avoid impacts on population centers by accidentally or intentionally generated debris. For WSMR launches, typical observed limits on risk to nearby population centers are land impact probabilities of $< 10^{-5}$ on-range and $< 10^{-7}$ off-range, resulting in casualty expectations of $< 10^{-7}$ to 10^{-9}.

Models, run sequentially or in parallel, are designed to compute risks based on estimating both the probabilities and consequences of launch failures as a function of time into the mission. Inputs and external data bases include data on mission profile, launch vehicle specifics (e.g., solid or liquid rockets, stages, configuration), local weather conditions and the surrounding population distribution. Given a mission profile, orbital insertion parameters and desired final orbit, the risks will vary in time and space (see Ch. 10). Therefore, a launch trajectory optimization is performed by the Range for each proposed launch, subject to risk minimization and mission objective constraints. The debris impact probabilities and lethality are then estimated for each launch considering the geographic setting, normal jettisons, failure debris and demographic data to define destruct lines to confine and/or minimize potential public risk of casualty or property damage.

The National Ranges use either a circular or an elliptical footprint dispersion model to analyze vacuum and wind-modified instantaneous impact points (IIP) from both normal stages jettisoned during launch and launch debris (failure or destruct).[1] The debris dispersal estimates generally assume bivariate Gaussian dispersion distributions.[19,21] Risk contours are estimated as impact probabilities or casualties expected per unit area centered on the II (nominal impact points) or on a specific site (land, community or Range) of interest. All these models are similar in approach, but quite site-specific in the use of databases, which depend on Range location and on the geographic area and associated population distribution at risk. The models may be run either as simulation to assist in analyzing and selecting launch options, or can be run in real-time, to monitor a launch operation.

The information and risk computation logic flow depicted in Figs. 9-2, 9-3 are used in a computer program developed to calculate relative risks to population centers along the flight corridor ground-track, namely the LARA - Launch Risk Analysis program and its later upgrades.[19,21] The LARA program is in use at WSMC and PMTC and is being introduced at ESMC. Figure 9-4 shows a sample real-time debris footprint display monitored by Range Safety Officers at WSMC during each launch operation. It is based on computed and wind-corrected trajectory and LARA impact patterns moving with the tracked vehicle and their position relative to the fixed, prescribed destruct and impact limit lines. If the failed vehicle encroaches these lines, a destruct decision must be made or withheld according to clearly formulated destruct criteria.

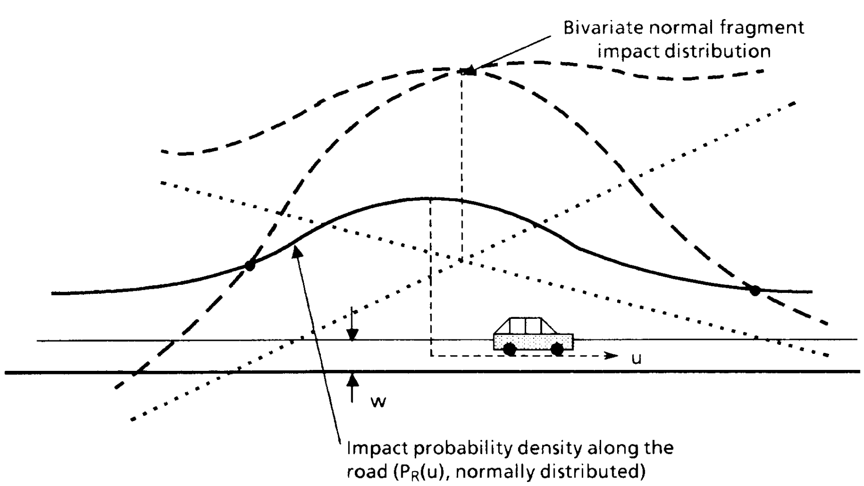

FIGURE 9-2. IMPACT PROBABILITY COMPUTATION FOR ROADS

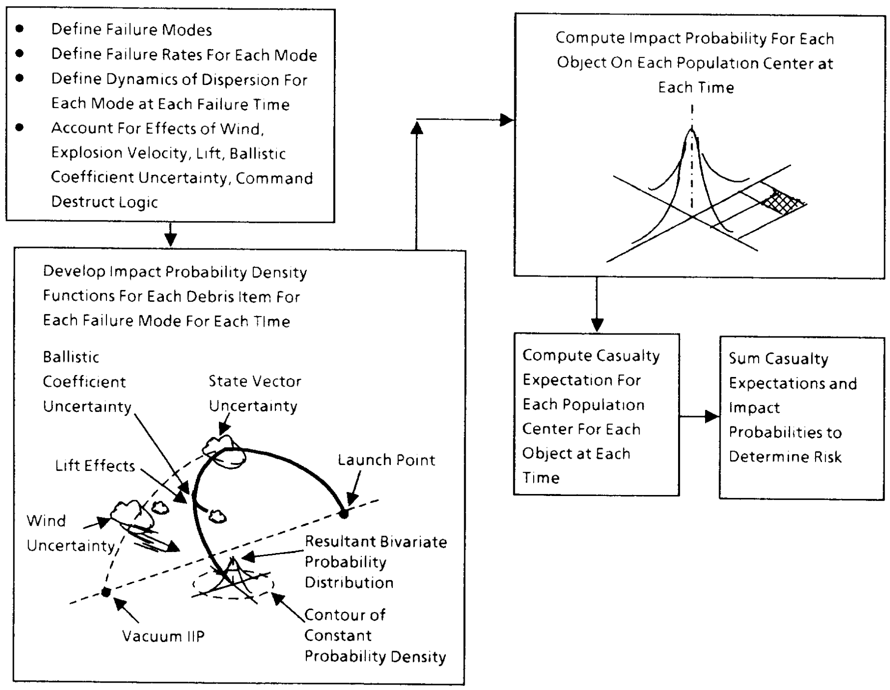

FIGURE 9-3. RISK COMPUTATION

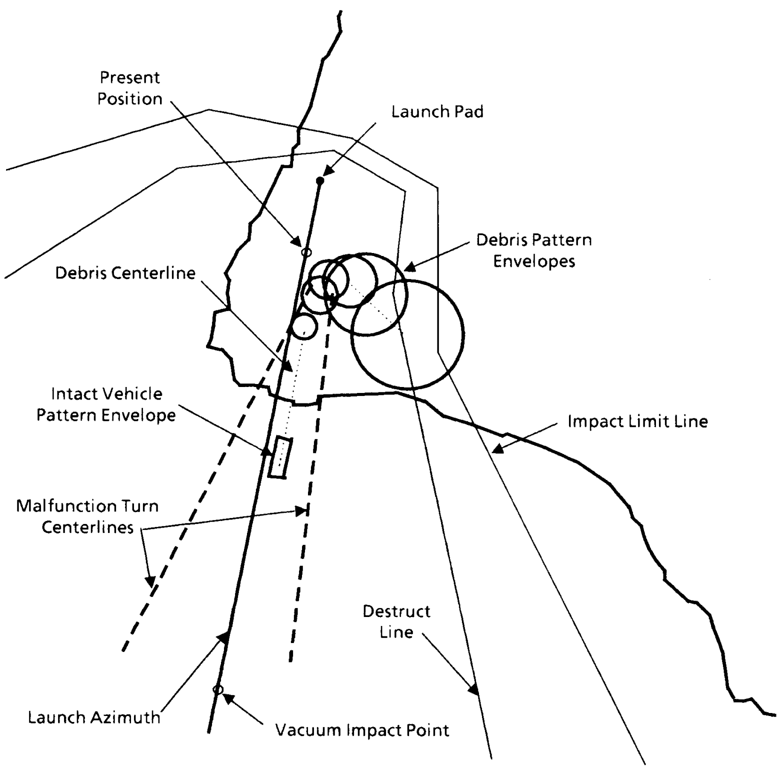

FIGURE 9-4. REAL TIME DEBRIS FOOTPRINT DISPLAY

Since WSMR is a land-based Range, safety considerations are particularly important in authorizing tests that might endanger the public. Computer models in use at the Range support pre-mission simulations of normal and failed flights, as well as real-time tracking and destruct decisions based on vacuum and drag corrected IIPs. The library of risk computation and utility codes used by Range Safety include: SAFETY.SITE (generates scaled maps of the range and tracking installations), SAFETY.DMA (converts maps to desired coordinate scale), SAFETY.GIP (predicts both vacuum and drag corrected impact coordinates) and several other external modules for population data and impact point prediction. The WSMR Hazard Analysis method and its application to launches of sub-orbital vehicles with recoverable payloads was illustrated in a 1986 study.[2b] Other risk analyses have been performed for specific tests and launch vehicles based on tailored models using the vehicle characteristics and launch geometry.

WSMC has an extensive array of software developed to assist in evaluating hazards to facilities and population centers and devising appropriate risk control options.[19-21] These include: LARA, CONDEC (Conditional Casualty Expectation), RBAC (Risk Based Destruct Criteria), ACE (which combines CONDEC and RBAC to compute casualty expectation along arbitrary destruct lines), SLCRSK and LCCRSK (which compute probabilities and expected magnitude of damage to the reinforced launch control center and to other VAFB facilities, such as SLC-6, for certain launch azimuths).[20] Other special purpose models are: BLAST, to assess explosion shock wave far-field impacts; SABER, to evaluate supersonic boom effects; REEDM, for hot toxic gas predictions and a series of cold spill toxic prediction algorithms for toxic releases.

ESMC has its own library of codes used to support launches as pre-flight simulations and real-time monitoring and display. These include: BLST, similar to BLAST above; COLA, a collision avoidance program used to ensure that a proposed launch will not jeopardize any satellite in orbit; RAID, the major real-time Range Safety program which displays the ELV position and II based on tracking data; RSAC and RSTR, which provide plots in site-centered coordinates; REED, used for launch and post launch environmental analysis of exhaust cloud effects; RIPP, an interactive impact point and destruct line plot and RSIP (Range Safety Impact Predictor), which computes impact position parameters along the trajectory with and without wind data. Other codes are used to assess the fate of an errant ELV, such as RSPFT (Range Safety Powered Flight and Turns) and RSTT (Range Safety Tumble Trajectory), to predict malfunction behavior for each vehicle type and nominal trajectory; and RSMR, which computes the maximum pad-to-impact range for a vehicle and its debris. External modules are used to update wind corrections (RSRK, for Range Safety Radiosonde Data) and assess risks to ocean traffic (RSSP or Range Safety Ship Hit Probability).

For any developmental vehicle, safety assessments must precede flight testing and launch approval. For example, the new commercial launch vehicle Conestoga has been flight tested recently; Conestoga failure modes and rates were based on previous experience with the Aries rocket and the Minuteman I second stage motor, which were reconfigured as the Conestoga. Special attention was given to the possibility of impact and damage to off-shore oil platforms in the Gulf Area, given the flight path, ground track and safety corridor for Conestoga under a range of plausible vehicle failure scenarios and weather conditions.(36) However, because of redesign of the Conestoga, some of the safety assessments are being re-evaluated for launches from WFF.

The hazard models used by NORAD and AFSC to estimate far-field public risk exposure (i.e., for assessing the probability that a failed vehicle, re-entering second stage or debris will impact in CONUS and/or foreign countries and cause damage and casualties) were originally developed by the Aerospace Corporation.(34,35) These re-entry risks for second and upper stages and for low-orbit payloads appear, typically, to be several orders of magnitude larger than launch and orbit insertion risks (see Ch.7, Vol.2) because they integrate world-wide casualty expectation. Impact probabilities and casualty expectations for a specific country are much smaller and proportional to their area and population contribution to the integral.

Overflight risks are also a modeling and operational planning concern for Range Safety: some trajectories may traverse Japan, Australia, Africa and South America (see Ch.10 also). Table 9-2 summarizes extant risk results, namely the probabilities of land impacts and projected casualties for typical ELV's on allowed azimuths for ESMC launches over water.(37) These flights must protect the "African Gate" during overflight(see also Ch.10).

This performance gate defines the maximum cross-range deviations from the nominal overflight trajectory which may be tolerated without termination action. These are well within the destruct limits to better protect populated areas at risk in case of abnormal vehicle performance.

To place the criteria and goals for public risk exposure per space launch in perspective, it is instructive to compare them with other common, but voluntarily assumed or socially accepted transportation risks (see also Ch.5, Vol.2 and Ch.8). Ref. 29, published prior to the 1986 Challenger accident, estimated the casualty probability per flight for commercial air carriers to be 6.6 x 10^{-5} (based on 1972-74 data) vs. 1-3 x 10^{-5} for the Space Shuttle (to compare respective risks from an STS failure with and without a destruct system on-board). For comparison, the 1982-84 transportation accident statistics give fatality rates per 100 million passenger-miles of .02 for inter-city buses, .04 for airlines and .07 for railroads. These values correspond to a casualty probabilities of 2-7 x 10^{-10} per mile. This probability must be converted to units of interest to space operations (per launch event or per year) and then further normalized to the exposed population and the area at risk. Further, utility/benefit considerations must be brought to bear for a meaningful comparison of public transportation with space transportation risks.

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